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MATHEMATICAL AND EXPERIMENTAL ANALYSIS OF SOLAR TUNNEL DRYER FOR DRYING BEEF AS A BIOLOGICAL PRODUCT

V. SUBBIAN[1], V. NADANAKUMAR[2*], R. CHRISTUPAUL[3] & K. KALIDASA MURUGAVEL[4]

[1]*Department of Mechanical Engineering, KNSK College of Engineering, Nagercoil, Tamil Nadu, India*

[2,3]*Department of Automobile Engineering, Hindustan Institute of Technology and Science, Chennai, India*

[4]*Department of Mechanical Engineering, National Engineering College, Kovilpatti, Tamil Nadu, India*

ABSTRACT

This work analyses the performance of a solar tunnel dryer for drying beef, under forced convection by using a DC blower run by a photovoltaic panel (200w). An experimental setup of solar tunnel dryer has been designed and fabricated. Experiments have been performed during summer season. The system is operated between 30ºC and 69ºC. The dryer is simple in construction, at a low cost, with locally available materials. The performance of the designed drier is evaluated by carrying drying experiments at Nagercoil, Tamilnadu, India (8.1700°N, 77.4300°E). Response surface methodology was used to investigate estimation of capacity optimization and acceptability using desirability for single product. The independent variables or responses were time, air temperature and solar radiation. ANOVA also showed that the lack of fit was not significant for all response surface models, at 95% confidence level.

KEYWORDS: Solar Energy, Solar Dryer, Experimental Performance, Drying Capacity & Response Surface Methodology

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Original Article

INTRODUCTION

Beef, is one of the third most widely consumed meats in the world, accounting for about 25% of meat production worldwide, after pork and poultry at 38% and 30%, respectively. A drying process is needed to preserve and inverse the shelf life of such edible end products, an open drying process under direct sunlight is an efficient system of utilizing solar energy (Bala and Woods 1994; Rathore and Panwar 2011). Effectiveness of continuous solar dryer, integrated with desiccant thermal storage for drying cocoa beans to improve drying time and specific energy consumption has been reported (Sari et al 2015). This work was carried out using the simulation method, which is suitable in the design of passive solar dryers to find the optimum mass air flow (Duran et al 2015). A report on cabinet dryer with packed bed PCM, capable of storage of thermal energy in the form of latent heat and sensible heat during day time had been presented by (Dilip and Pratibha 2015).

Reviews of various types of solar dryers for drying various commodities were made, and a computer technology was designed leading to many simulation tools to investigate the process characteristic of any system, before its fabrication (Mahesh et al 2016). This paper presents an experimental investigation and economic evaluation of a new mixed mode solar greenhouse dryer for drying red pepper and grape in open sun and under greenhouse effect in the falling rate period (Aymen et al 2015). This paper presents the drying efficiency of the dryer, which was 35.7% while the total specific energy (including solar radiation) was 9.475MJ. kg-1 of water evaporated (Yefri et al 2015). Mustayen et al (2014)had studied the performance of different solar dryers.

This paper presents an evaluation of two fitting methods applied for thin layer drying of Capegooseberry (Erkan, 2016). Many studies have been reported on solar drying of various products (Fernando et al. 2015, Xiaroran et al. 2015).

Out of the literature survey conducted, it is observed that tunnel dryers were not employed so far the studies on drying beef. Response surface methodology is also powerful to analyze the performance characteristics of the system. This work on tunnel dryer brings in to light, the combined effects of drying of beef using tunnel dryer and analysis through RSM. Interpretations have been developed to study the performance of the proposed system theoretically and to justify it practically.

MATERIALS AND METHODS

Experimental Setup

Heat by Solar radiation also helps drying the products. The dryer, essentially consists of a flat plate air heating collector and a tunnel drying unit as shown in the Figure 1. Both the collector and the drying unit are covered with UV stabilized plastic sheets. The product is placed in a single layer on a wire mesh inside the tunnel drier. Thermocol, pebbles and sawdust are used as insulation materials in different layers to reduce the heat loss from the bottom of the drier. Thermocouples are provided to measure the temperatures during drying period. A chimney is provided to maintain the air-flow at the end of the dryer towards atmosphere. The whole system is placed horizontally on a raised platform. Atmospheric air enters the system through the inlet by forced convection. Solar radiation passes through the transparent cover of the collector and heats the absorber. Ambient air enters through the collector by the dc blower run by power from photovoltaic cells. Heat is transferred from absorber plate to air above the collector; heated air from collector while passing over the products absorbs moisture from the products. This enhances the drying rate, and the temperature in the drier rises to the range of 30°C to 69°C. Schematic view of the solar tunnel dryer with dc blower is shown in Figure 2.

Figure 1: Photographic View of Solar Tunnel Dryer

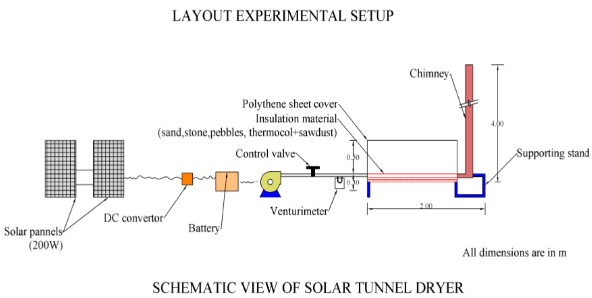

Figure 2: Shows a Schematic View of the Solar Tunnel Dryer with dc Blower

Experimental Procedure for Drying Products

This study deals with research carried out on solar drying and optimizing for beef. All the important parameters affecting the performance of the drier were measured. A thermocouple was used to measure the drying air temperature along the flow direction of the air inside the dryer, and a solar meter was used to measure the incident radiation. The ambient temperature of the air is measured with a thermometer. The velocity of drying air was measured by an anemometer. Weight loss of the product during drying period was also measured with an electronic balance. The direct sun dried samples (of 1kg) were also weighed. All these data were recorded at 1hour intervals. The samples of drying products were placed on the wire mesh of the drier in a single layer. Experiment was started at about 6.00 am and was stopped at about 6.00 pm. To compare the performance of the tunnel drier with that of the direct sun drying, samples of beef were placed on trays in single layer inside the drier.

The thermal efficiency of the dryer is given by

$$\eta = (m \times L)/(\mathrm{A} \times \mathrm{I_S}) \tag{1}$$

The moisture ratio is given as follows:

$$\mathrm{MR} = \frac{\mathrm{Mt} - \mathrm{M_e}}{\mathrm{M_0} - \mathrm{M_e}} \tag{2}$$

Where, MR is the dimensionless moisture ratio, Mt, Me and M0 are the moisture content at any time, t is drying time, Me is the equilibrium moisture content and M0 is the initial moisture content in kg of water/kg, respectively. However, MR is simplified to Mt/M0 as suggested by (Kamil et al 2006), due to the continuous fluctuation of the relative humidity of the drying air during the drying process. The drying rate constants and coefficients of models were estimated using a nonlinear regression procedure.

Table 1: Thin-Layer Drying Models Given by Various Workers for Drying Curves

Model name	Model	Reference
Newton	MR = exp(-k t)	Henderson(1974)
Page	MR = exp(-k t^m)	Diamantes and Munro(1993)
Henderson and Pabis	MR = a exp(-k t)	Zhang and Litchfield(1991)
Wang and Singh	MR = 1+ at +bt^2	Wang and Singh(1978)

Levenberg–Marguardt and the statistical validity of models were evaluated and compared by means of the coefficient of determination R2, mean relative percent deviation EMD, root mean square error ERMS and reduced chi-square χ 2. These comparison criteria were calculated as follows Henderson (1974).

$$\mathrm{E_{MD}} = \frac{100}{\mathrm{N}} \sum_{\mathrm{i=1}}^{\mathrm{N}} \frac{|\mathrm{M_{R,ex,i}} - \mathrm{M_{R,pre,i}}|}{\mathrm{M_{R,ex,i}}} \tag{3}$$

$$\mathrm{E_{RMS}} = \left[\frac{1}{\mathrm{N}} \sum_{\mathrm{i=1}}^{\mathrm{N}} \left(\mathrm{M_{R,ex,i}} - \mathrm{M_{R,pre,i}}\right)^2\right]^{1/2} \tag{4}$$

$$\chi^2 = \frac{\sum_{\mathrm{i=1}}^{\mathrm{N}} \left(\mathrm{M_{R,ex,1}} - \mathrm{M_{R,pre,i}}\right)^2}{\mathrm{N} - \mathrm{Z}} \tag{5}$$

$$\mathrm{R}^2 = \frac{\sum_{\mathrm{i=1}}^{\mathrm{N}} (\mathrm{M_{R,exp,i}} - \mathrm{M_{R,mean}})2 - \sum_{\mathrm{i=1}}^{\mathrm{N}} (\mathrm{M_{R,exp,i}} - \mathrm{M_{R,pre,i}})^2}{\sum_{\mathrm{i=1}}^{\mathrm{N}} (\mathrm{M_{R,exp,i}} - \mathrm{M_{R,mean}})^2} \tag{6}$$

Where, MR, ex, i is the ith experimental dimensionless moisture ratio; MR, pre, i is the ith predicted dimensionless moisture ratio; N is the number of observations; and Z is the number of constants. R2is used as the primary comparison criterion for selecting the best model among the four models. Also, a model is considered better than another, if it has a lower value of the EMD, ERMS and χ 2. During drying, water at the surface of the substance evaporates and water in the inner part migrates to the surface to get evaporated. The ease of this migration depends on the porosity of the substance and the surface area available. Other factors that may enhance drying are: high temperature, high air speed and low relative humidity. However, for drying the items like fish, meat, yam chips and plantain chips etc., excessive heating must be avoided, as it spoils their texture and quality.

RESULTS AND DISCUSSIONS

For Beef

The variation of solar radiation and thermal efficiency during experimentation is shown in Figure3. Maximum solar intensity of 880 Wm-2 had been observed. The moisture content and the moisture removal process are fully depending upon the temperature and mass flow rate. The moisture is reduced to 2.43% shown in Figure 4. The thermal efficiency is also varying from 0% to 47.26 %. The maximum thermal efficiency is 63%, as shown in Figure 3.

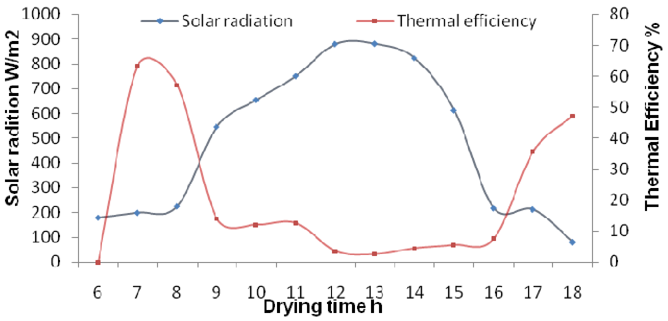

Figure 3: Variation of Solar Radiation and Thermal Efficiency with Drying Time for Beef

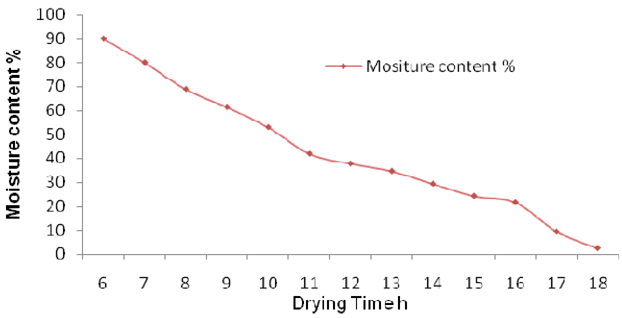

Figure 4: Variation of Moisture Content and Drying Time for Beef

Fitting of the Drying Curves for Beef

Table 2 lists the estimated parameter and comparison statistics of four drying models, for solar drying of beef for typical experiments. For solar drying, all models other than the Newton model provided an adequate fit to the experimental data with a value for R2 is 0.99383, indicating a good fit for Newton model.

Table 2: Thin-Layer Estimated by Non-Linear Regression and Model Performance Values

Model Name	Constant	R^2	E_{MD}	E_{RMS}	χ^2
Newton	K = 0.07575	0.99383	8.0180	0.02330	0.000592
Page	K= 0.09742 m= 0.6192	0.97782	12.918	0.04418	0.002343
Henderson & Pabis	a= 1.2045 k= 0.1043	0.98062	9.538	0.0413	0.002047
Wang & Singh	a=10.768 b= -1.300	0.99067	10.570	0.0286	0.000985

From the above results, it is observed that all model values are found to be less as compared with Newton models, and the Newton model is suitable for the determination of grater in the coefficient of R2 values for the case of lower air flow rate model.

Response Surface Methodology Modeling and Statistical Analysis

In response surface methodology, central composite design method is used for the optimization purpose. The method was introduced by (Box and Wilson 1951). Central Composite Design (CCD) is the most popular response surface method used to predict the output response with respect to input parameters. In this method, the relationship among the independent variables, time, air temperature and solar radiation were expressed mathematically in the form of polynomial model. Response surface regression (Design- Expert version 9.0.6) statease Inc., Minneapolis, USA was performed on the collected data, while the thermal efficiency and moisture content was considered as response. The experimental results were analyzed using the central composite design method, to obtain the best fit empirical mathematical model. To visualize the combined effects of three factors on any response, the response surface and contour plots were generated for each of fitted models of three independent variables.

The Coefficients for Predicted Models for Beef

Table 3: Analysis of Variance and Coefficients for Predicted Models

Source	DF	Thermal Efficiency(TE)			DF	Moisture Content(MC)		
		Coefficient	Sum of Squares	P Value		Coefficient	Sum of Squares	P Value
Model	9	-8.04	943.51	0.0084	9	47.86	9431.02	< 0.0001
A	1	74.49	173.92	0.0149	1	-39.77	3046.70	< 0.0001
B	1	-81.48	183.29	0.0131	1	4.12	21.50	0.0367
C	1	68.98	272.22	0.0043	1	-7.68	102.01	0.0001
AB	1	161.82	284.34	0.0038	1			
AC	1	-144.47	483.59	0.0006	1			
BC	1	141.38	281.84	0.0039	1			
A^2	1	-71.10	145.88	0.0228	1			
B^2	1	-62.92	227.90	0.0073	1			
C^2	1	-70.57	217.11	0.0083	1			
Residual	10		202.00		10		66.23	
Lack of Fit	3		202.00		3		66.23	
Pure Error	7		0.000		7		0.000	
Total	19		1145.52		19		9497.25	
R^2		0.8237				0.9930		
Adj-R^2		0.6649				0.9917		
Pre-R^2		-30.3740				0.9859		
Adeq Precision		6.673				80.203		

$p < 0.05$ is significant at $\alpha = 0.05$; lack of fit is not significant at $p > 0$.

The type of polynomial model obtained for the responses are linear and quadratic. Two different response surface plots (Figure 5-8) were illustrated by maintaining one of factor constant for each Figure. The effects of independent variables on the responses are represented in perturbation graphs (Figure 5). The increase of time and solar radiation had an increased thermal efficiency response. The linear effect of air temperature in Table 3 shows negative effect on thermal efficiency. Figure 6also indicates the more pronounced effect of thermal efficiency compared to time and air temperature. The quadratic terms of air temperature have negative effect on thermal efficiency. The interactive effect of BC has positive effect on thermal efficiency. The effect of independent variables on the responses as represented in perturbation graphs (Figure 7) revolves that, time and solar radiation showed lowering effect with reference to moisture content. The type of polynomial model obtained for the responses are linear and quadratic model in moisture content. The linear effect of the variable in Table 3 shows time, and solar radiation had negative effect on moisture content. Figure 8 indicates decrease in moisture content with increase of time and temperature at process duration. The model as fitted provides an adequate approximation to the true system.

$$\text{Thermal efficiency} = +26.38+73.03*A-128.56*B+6.69*C+62.52*AB-4.48*AC+149.93*BC -189.59*A^2-37.99*B^2+28.17*C^2$$

$$\text{Moisture Content} = +29.68-13.69*A-16.34*B+3.94*C+36.53*AB-4.07*AC-2.87*BC-6.18*A^2 -0.070*B^2+13.86*C^2$$

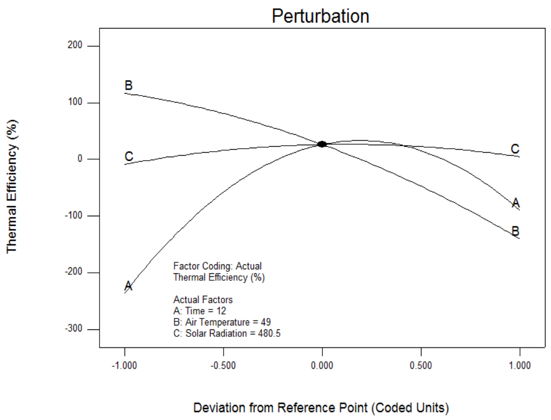

Figure 5: Perturbation Graph Showing the Effect of Independent Variable on Thermal Efficiency (Beef)

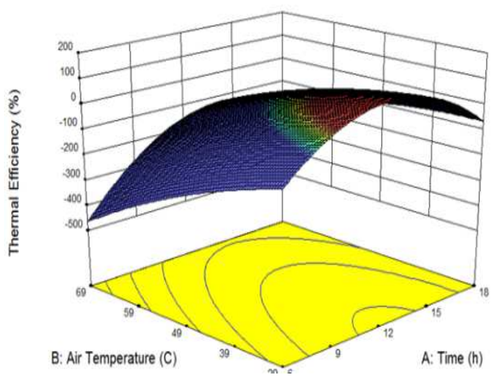

Figure 6: Response Surface and Contour Plots for Thermal Efficiency (Beef)

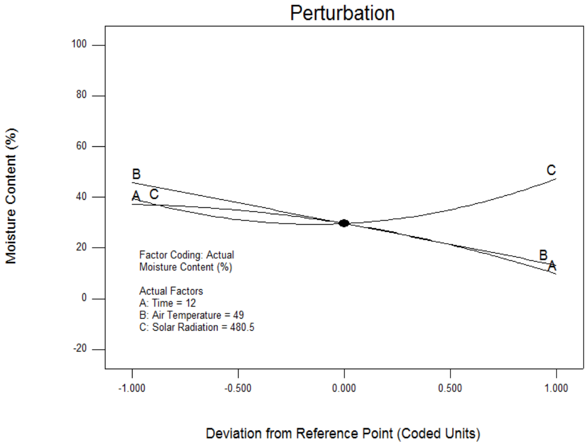

Figure 7: Perturbation Graph Showing the Effect of independent Variable on Moisture Content (Beef)

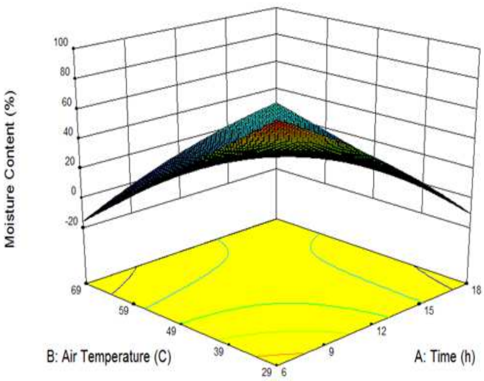

Figure 8: Response Surface and Contour Plots for Moisture Content (Beef)

CONCLUSIONS

In this work, the aim is to perform an experimental analysis using solar dryer for drying beef. This work contains the literature review, solving methodology, theoretical analysis and response surface methodology for solar air heater, in which, the economic analysis, fabrication and experimental analysis of the system are completed. After performing the experimental analysis, results such as thermal efficiency and moisture content with respect to time and solar radiation had been plotted. Response surface methodology is a powerful tool for modeling of extrusion processing of drying products. Thermal efficiency and moisture content for the drying of beef can be predicted by the model as fitted. The predicted values obtained from the perturbation and contour plots were closer to the experimental values in the graphical optimization technique.

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